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Appropriate structural unfired earth masonry units

Dr Daniel Maskell MEng, PhD¹, Dr Andrew Heath BSc(Eng), MS, PhD, CEng MICE, FHEA¹
and Prof Pete Walker BSc, PhD, MIEAust CEng, MICE CEng¹

¹BRE Centre for innovative Construction Materials,
Department of Architecture and Civil Engineering,
University of Bath,
Bath,
United Kingdom

Corresponding Author: Dr Daniel Maskell, D.Maskell@bath.ac.uk

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Abstract

Modern earth masonry utilises conventional methods of extruded fired brick manufacturing for the manufacture of unfired earth bricks. However, the bricks produced currently are not generally recommended for structural applications due to their loss of strength under elevated moisture contents. In response to this loss in strength bricks can be chemically stabilised, typically by the addition of cement or lime. However, the use of such binders typically negates the reduced environmental impact of using unfired brick, which is often the initial driver.

The research presented in this paper considers the improvement in compressive strength that can be achieved through the addition of a range of pozzolanic binders as well as their associated embodied energy and carbon. This allows for a holistic comparison of material selection based on meeting the minimum structural requirements of the masonry units while improving on the embodied impact of equivalent units currently used. The study shows that an unfired brick with the addition of lime and metakaolin achieves a compressive strength over 6MPa when dry and over 1MPa following complete saturation whilst reducing the global warming potential by over 30%. This paper demonstrates that stabilised unfired bricks can be practically viable, structurally suitable and environmentally beneficial.

1 Introduction

There are growing concerns over the embodied environmental impact of construction materials (Sturgis and Roberts, 2010). Whilst earthen forms of construction have been used for thousands of years, there is a renewed interest due to its low embodied impact (Morton, 2006). For this benefit to have a national impact modern methods of production and construction with earth are required. Modern earth masonry that uses commercial methods of brick manufacture can be utilised for unfired earth brick production (Morton, 2008 and Heath et al., 2009).

Sourani and Sohail (2011) identified 12 barriers to the adoption of sustainable forms of construction including:

- insufficient/confusing guidance, tools, demonstrations and best practice;
- separation between capital budget and operational budget;
- resistance to change;
- insufficient integration and link-up in the industry.

Traditional forms of earthen construction, such as rammed earth and cob, struggle to overcome many of these barriers. Adopting a masonry form of construction for earth, that has similar physical and mechanical properties to conventional forms will help, as there can be a relatively simple replacement of existing solutions. This will help to overcome resistance to change and lack of understanding. The barriers concerning capital budget and cost, lack of sufficient time, insufficient link with industry can be addressed through the use of current mainstream manufacturing techniques.

There are currently no structural design codes published by either ISO or Eurocodes for earthen materials, though, ASTM recently published ASTM E2392 for Earthen Wall building systems.

Suitable standardised codes for the material will provide guidance for compliance that can be regulated, which will lead to a greater understanding and potential for development.

Commercially extruded earth brick production uses similar methods of manufacture as fired brick units, but the high energy firing process is omitted. The method has some benefits over Compressed Earth Bricks (CEB), due to the existing manufacturing techniques and the quality and consistency of bricks produced. This produces conventional sized bricks and results in a wall thickness of approximately 100mm for internal partitions and inner leafs. Heath et al. (2012) demonstrated the structural feasibility of unfired clay bricks for use in two to three story domestic buildings where lightweight concrete blocks, with a compressive strength of 2.9MPa, would typically be specified. However, at elevated moisture contents, the compressive strength reduces which can lead to complete loss of structural integrity (Heath et al., 2012). When walls constructed of thin walled earth masonry are subjected to these conditions, even as an accidental load case, then clearly disproportionate collapse could occur. This has led to defined minimum strength criteria for the unfired brick units as 2.9 MPa under 'dry' conditions and 1.0 MPa under 'wet' conditions (Maskell et al., 2014). 'Dry' conditions are ambient temperatures and relative humidity and 'wet' conditions are following over 16 hours being fully submerged in water, relating to testing conditions within BS EN 771-1:2003 (2005).

Stabilisation has been investigated as a method of improving the mechanical properties of unfired masonry units (Maskell et al., 2014 and 2015). There is a range of potential methods of stabilisation mechanisms, but these typically involve the addition of chemical stabilisers. While this could ensure structural feasibility, there is likely to be change in the environmental impact of the unfired masonry units that might negate the original intention of their use. This paper presents a range of stabilisation mechanisms and discusses their impact on the mechanical strength and embodied environmental credentials.

The aim of this paper is to present a low impact earthen masonry unit that can be viably structurally used. Therefore the objective of the research described in this paper is the development of a stabilised masonry unit that meets minimum compressive strength requirements. The use of these stabilisers will have an associated environmental impact, therefore any stabilised masonry unit

shouldn't be environmentally worse than a conventional masonry unit. Therefore, an additional objective of this paper is to define a maximum allowable environmental impact based on the lowest impact of a conventional masonry unit. The environmental impact of the stabilised earthen masonry units can then be calculated and compared to the maximum allowable impact of a conventional masonry unit. Defining these structural and environmental criteria and investigating various stabilised masonry units against these criteria will achieve the aim of an environmentally appropriate structural unfired earth masonry unit.

2 Background

2.1 Stabilisation

Stabilisation offers a method of improving various properties of soil and is commonly used in geotechnical applications, including ground improvement. Stabilisation for earthen construction materials generally focuses on the improvement of mechanical properties of blocks intended for structural use and increased moisture resistance (Maskell et al., 2014 and 2015). Stabilisation includes mechanical, physical and chemical processes; however, their implementation changes the environmental impact of the unfired earth brick unit. Generally physical and mechanical methods of compaction are determined by the method of manufacture of earthen bricks. Compactive effort for CEBs can be readily changed to improve the mechanical properties (Walker 2004). The physical removal of moisture by increasing the Initial Curing Temperature (ICT) has been shown to increase the compressive strength (Heath et al., 2009), as well as enabling some chemical reactions to occur (Maskell et al., 2015). Comparably there has been significant work on chemical stabilisation methods that facilitates chemical reactions between the soil and stabiliser (Walker 2004, Reddy and Gupta, 2006, Oti et al., 2009, Maskell et al., 2014 and 2015.). This is largely due to the need to meet structural requirements of the unfired masonry as discussed by Heath et al., (2012). The greatest barrier to adoption of unfired earth masonry is its reduction of strength when exposed to elevated moisture conditions that could occur in accidental conditions including flood or burst water pipes. This

strength reduction can only be overcome by chemical stabilisation that maintains minimum mechanical performance at high moisture levels.

2.2 Environmental impact

There are many varying approaches to measuring the environmental impact of construction materials and as such the quality of information and values assigned to materials varies throughout the literature. Life Cycle Analysis (LCA) is the only method of considering the environmental impact that has been standardised through BS EN ISO 14040:2006 (2006) and BS EN ISO 14044:2006 (2006). The LCA methodology was used by BRE (2007) to create Environmental Profiles for various construction materials and continues to be used within the construction industry. The environmental profiles can be used to compare building materials based on a wide range of environmental impacts. The methodology provides rules and boundaries to an LCA specifically considering building products. The methodology, as with LCA, uses a Life Cycle Inventory (LCI), that quantifies the input and outputs of the LCA. Typically, the Embodied Energy (EE) and Global Warming Potential (GWP) are reported for construction materials (Hammond and Jones, 2008) and will be the focus of this paper.

There is limited publicly available literature on the LCI of conventional masonry units, generally due to the commercial nature of competing products. Therefore, generic data, such as the Inventory of Carbon & Energy (ICE) (Hammond and Jones, 2008) or Ecoinvent (Weidema et al., 2013), are commonly used instead for comparative LCA. The use of generic datasets, using average industry values, has been justified by Hammond and Jones (2008) for construction materials.

2.3 Summary

An appropriate structural unfired earth masonry unit is defined as one that can meet the minimum structural requirements and better the equivalent environmental impact of a conventional masonry unit. While it has been shown that various methods of stabilisation, through the addition of chemical additives, are able to achieve the desirable mechanical strength properties, there has been little consideration to the impact of these additions to the environmental impact. This combined approach

is the focus of this paper with the aim to identify the most appropriate unfired earth structural masonry unit.

3 Materials and methods

3.1 Materials

This paper will consider unfired stabilised extruded earth masonry units as previously discussed by Maskell et al., (2014 and 2015). The masonry units were manufactured using the same extrusion process to commercial fired brick production without the final firing. Maskell et al., (2014 and 2015) investigated the effects of the addition of cement and lime with further testing considering additional metakaolin.

Based on 100mm wall thickness (typical for fired bricks and concrete blocks) and assuming the densities do not significantly change with the inclusion of a stabiliser, the maximum allowable amount of stabiliser can be estimated. This is based on not exceeding the environmental impact of conventional masonry units. The maximum allowable mass fraction of cement and lime is therefore approximately 8%. Therefore, specimens with 3%, 5% and 8% cement and lime specimens have been considered. Metakaolin is dehydroxylated kaolin and is a reactive pozzolan and its addition allows for an improvement of mechanical properties, but itself will incur a negative environmental impact. Therefore specimens with 5% and 10% metakaolin addition to 5% cement and lime have been considered.

3.2 Methods

The mechanical properties and the environmental impacts of the specimens were assessed experimentally and numerically respectively. A full LCA is outside the scope of this paper, however a Life Cycle Inventory (LCI), which is one of the initial stages in a LCA could be approximated to assess the feasibility of the unfired stabilised masonry units.

3.2.1 Determination of mechanical properties

An estimation of the mechanical properties was determined by measuring the compression strength in both 'dry' and 'wet' conditions. Unfired bricks within commercial manufacture are typically dried for two days at 60°C. The effect of this drying was investigated experimentally by drying the different groups of bricks at 20°C, 60°C and 105°C and is considered during the environmental impact estimations. The strengths were measured at 28 days following the extrusion.

3.2.2 LCI of conventional masonry units

The EE and GWP of conventional masonry methods of wall construction, including fired clay bricks, AAC blocks and dense concrete blocks are compared in Table 1. These values are expressed with respect to the functional unit of the wall area, which would remain constant within the building design.

Table 1 Environmental impact of different wall constructions

Wall Construction	Wall Thickness	EE MJ/m ²	GWP CO2 eq /m ²	Source
Fired clay	100	600	44	Hammond and Jones (2011)
AAC block	100	220.5	15.1-23.0*	Hammond and Jones (2011)
Dense concrete block	100	152.2	20.9	Hammond and Jones (2011)
Rammed Earth	300	270	13.8	Hammond and Jones (2011)
CEB	190	29.3	-	Reddy and Jagadish (2003)
Extruded Earth Masonry	100	84	6.16	Hammond and Jones (2011) and Morton (2006)

Venta (1998) discusses the impact of brick manufacturing processes in Canada following the same extrusion process that has been considered by Heath et al., (2009) for unfired brick, reviewing each process as shown in Table 2. The energy attributed to each process has been converted to the functional unit, by assuming an internal wall thickness of 90 mm, as standard in Canada.

Table 2 Energy used in fired clay brick manufacturing, adapted from Venta (1998)

Process	EE MJ/m ²	GWP CO2 eq /m ²
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Raw material extraction	6.5	1.1
Raw material transport	3.2	0.5
Drying and firing	330.7	55.8
Preparation/forming/conveyance	248.6	42.0
In plant fuel	3.55	0.6
Total	592.5	100

From Table 1, it is clear that dense concrete block work has the least environmental impact of the conventional masonry units and therefore sets the benchmark that an alternative earthen-based material must outperform. For the masonry elements there would be an associated impact for the mortar of the units. Due to the variability in mortars that could be used, especially considering the varying suitability of novel mortars with earthen masonry (Lawrence et al., 2013), the environmental impact of mortars has not been considered and is outside the scope of this paper.

3.2.3 LCI of earthen wall construction

The EE and GWP of earthen wall construction are compared in Reddy and Kumar (2010) that state that there are three sources of EE within a rammed earth wall as constructed in India. These are transportation, mixing and compaction of the soil. Ignoring the energy required for transport (i.e. using factory gate values), values varied from 0.17 –7.43 MJ/m³. Although the wall thickness varied from 200mm to 400mm, the significant contribution was the addition of mechanical mixing. The energy in compaction in both cases is not accurately accounted for due to the manual processes used. Hammond and Jones (2011) also considered a non-specific rammed earth construction, assuming a density of 2000 kg/m³, which gives an EE of 900 MJ/m³ and GWP of 46 kg CO₂ eq/m³. These two values of EE for rammed earth are significantly different, indicating the difficulties of EE estimation when no audit trail is provided. This variation is expected to be due to variations in extraction of soil, assuming manual labour compared to a mechanised process. There are limited data on the environmental impacts of CEB. Reddy and Jagadish (2003) discuss the environmental impact of stabilised CEB and comments that a significant proportion of EE is attributed to the

inclusion of cement. Extrapolating from the results by assuming a linear relationship between the EE and cement content, gives an estimated EE of 154MJ/m³ for unstabilised CEB. The manufacturing process of fired clay bricks prior to firing is suitable, without any significant modification, for the production of unfired earth bricks. Morton (2006) demonstrated that there is an 86% saving in embodied carbon compared to conventional fired bricks, which is more than expected from Table 2. Although Morton (2006) does not provide environmental impact data on the unfired extruded bricks, this saving can be applied to data for fired bricks provided by datasets.

3.2.4 LCI of Stabilisers

The inventory analysis for different stabilisers focuses on cement, lime and metakaolin. The values of the inventory analysis of the different stabilisers are given in Table 3.

Table 3 Inventory Analysis for different stabilisers

Stabiliser	EE MJ/kg	GWP CO ₂ eq /kg	Source
Cement	4.5	0.74	Hammond and Jones (2011)
Lime	5.3	0.78	Hammond and Jones (2011)
Metakaolin	-	0.092	Habert et al. (2011)
	-	0.036	Jones et al. (2011)
	5.99	0.034	Calculated based on Ecoinvent data

Oti et al. (2009) discusses the environmental impact, including the EE and carbon dioxide emissions of various unfired clay brick mixtures with the addition of cement or lime, but in both cases with the addition of GGBS. While there is significant potential for the use of secondary stabilisers such as industrial by-products (Chen et al., 2010), there is limited supply (Heath et al., 2013).

Maskell et al., (2015) showed that the Initial Curing Temperature (ICT) can be significant with respect to the development of 'dry' and 'wet' compressive strength. The initial heat required for the curing should be accounted for in the inventory, but there is limited literature discussing the environmental

impact of heat used within the brick manufacturing process. A simplified approach for accounting of this additional heat can be considered based on the amount of heat that is used for the production of fired masonry units. Morton (2006) shows that 86% of the EE of a fired brick is attributed to the firing process which is typically for two days at 1100°C. Therefore, the environmental impact for this firing process can be calculated from which, the environmental impact per degree Celsius can be calculated. Although this makes significant assumptions with respect to the efficiency of the heating process and a linear relationship between the environmental impact and temperature, the validity can be assessed considering the specific heat capacity of the material. Minke (2006) states that the specific heat capacity of earthen material is 1.0 kJ/kg°C, which can be used to calculate the environmental impact for heating material. The EE and GWP of heating earth within an industrial furnace will be approximately 2.35kJ/kg/°C and 17×10^{-6} CO_{2eq}/kg/°C. Comparing the specific heat capacity of earth to the typical input heat energy would indicate that the furnace operates at an efficiency of 42%, which is within the range of furnaces efficiencies discussed by Hasanuzzaman et al. (2012).

There are limited data available from the literature regarding the environmental impact of metakaolin, with the exception of Habert et al. (2011), Jones et al. (2011) and Heath et al. (201). The approach by Habert et al. (2011) was to use data by Ecoinvent with gas for the heating sourced by biogas. While Habert et al. (2011) comment that this approach is in agreement with an industrial report, inspection of the Ecoinvent dataset shows that Kaolinite alone has a greater GWP than the resulting metakaolin. A similar approach for the calculation of metakaolin in Table 2 was taken using the data for Kaolin from Ecoinvent and using values calculated for heat. This calculation was done with consideration of the change in specific capacity (Robie and Hemingway, 1991) and the mass loss of Kaolinite by dehydroxylation for the formation of Kaolinite (Ilić et al., 2010). The heating of the Kaolinite accounts for 29% and 37% of the EE and GWP respectively. While the values for the EE and GWP of the metakaolin are in agreement with the figures presented by Jones et al. (2011), the validity of these figures remains in question.

4 Results and discussion

4.1 Compressive strengths

The measured compressive strengths of the masonry units are presented in Table 4.

Table 4 Compressive strengths of stabilised masonry units

Primary stabiliser	Mass Fraction	Secondary stabiliser	Mass Fraction	Compressive strengths at different curing and testing condition					
				20°C		60°C		105°C	
				Dry MPa	Wet MPa	Dry MPa	Wet MPa	Dry MPa	Wet MPa
	%		%						
Cement	3	-		4.67	0.00	4.48	0.00	4.56	0.00
Cement	5	-		7.40	0.42	7.21	0.57	6.84	0.74
Cement	8	-		6.46	0.37	5.74	0.13	5.80	0.19
Lime	3	-		4.00	0.00	3.71	0.24	3.78	0.43
Lime	5	-		3.40	0.00	4.13	0.66	5.12	1.02
Lime	8	-		5.02	0.00	5.51	0.77	4.46	0.55
Cement	5	Metakaolin	5	3.40	0.00	3.73	0.34	4.33	0.81
Cement	5	Metakaolin	10	3.09	0.31	3.72	0.46	4.26	0.56
Lime	5	Metakaolin	5	5.20	1.22	6.96	1.40	6.47	0.85
Lime	5	Metakaolin	10	6.60	2.33	6.42	1.82	6.34	1.95

There is interdependency between the soil type and stabiliser type with regard to the quantity that can achieve a maximum compressive strength. The addition of a chemical stabiliser affects the physical properties of brick, including the maximum dry density and Atterberg limits, compared to an unstabilised equivalent. Therefore, this will affect the energy for compaction (Reddy and Kumar,

2010) and extrusion, as well as any requirement for additional water or drying to achieve the optimum moisture content.

4.2 Environmental Impact

The data from the inventory analysis can be used to estimate the environmental impact of the different stabilisation treatments tested for the 'dry' and 'wet' compressive strength. This allows for a comparison of stabilisation treatments to be made not only based on structural properties but also environmental impact as well.

The environmental impact of the various stabilisers is displayed in Figure 1 and Figure 2. The environmental impact with respect to the EE and GWP has been calculated using the measured dry density of the masonry units. Figures 1 and 2 represents the specimens cured at 20°C and therefore there would be an additional environmental impact associated with curing at higher temperatures. While the increase in EE and GWP is not linear due to the varying densities, on average the values per degree Celsius increased 0.39 MJ/m^2 and $0.03 \text{ CO}_2 \text{ eq/m}^2$ respectively.

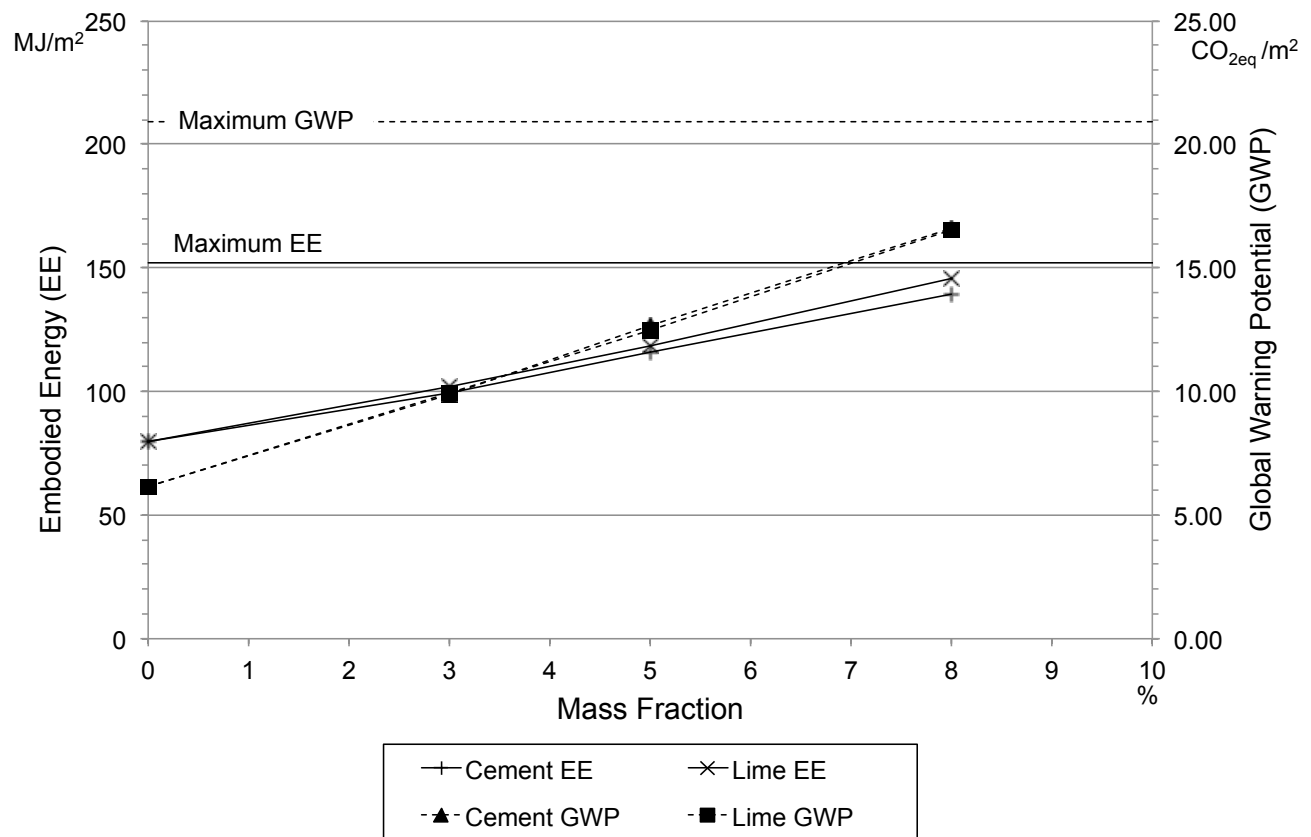


Figure 1: Embodied Energy and GWP of stabilised specimens cured at 20°C

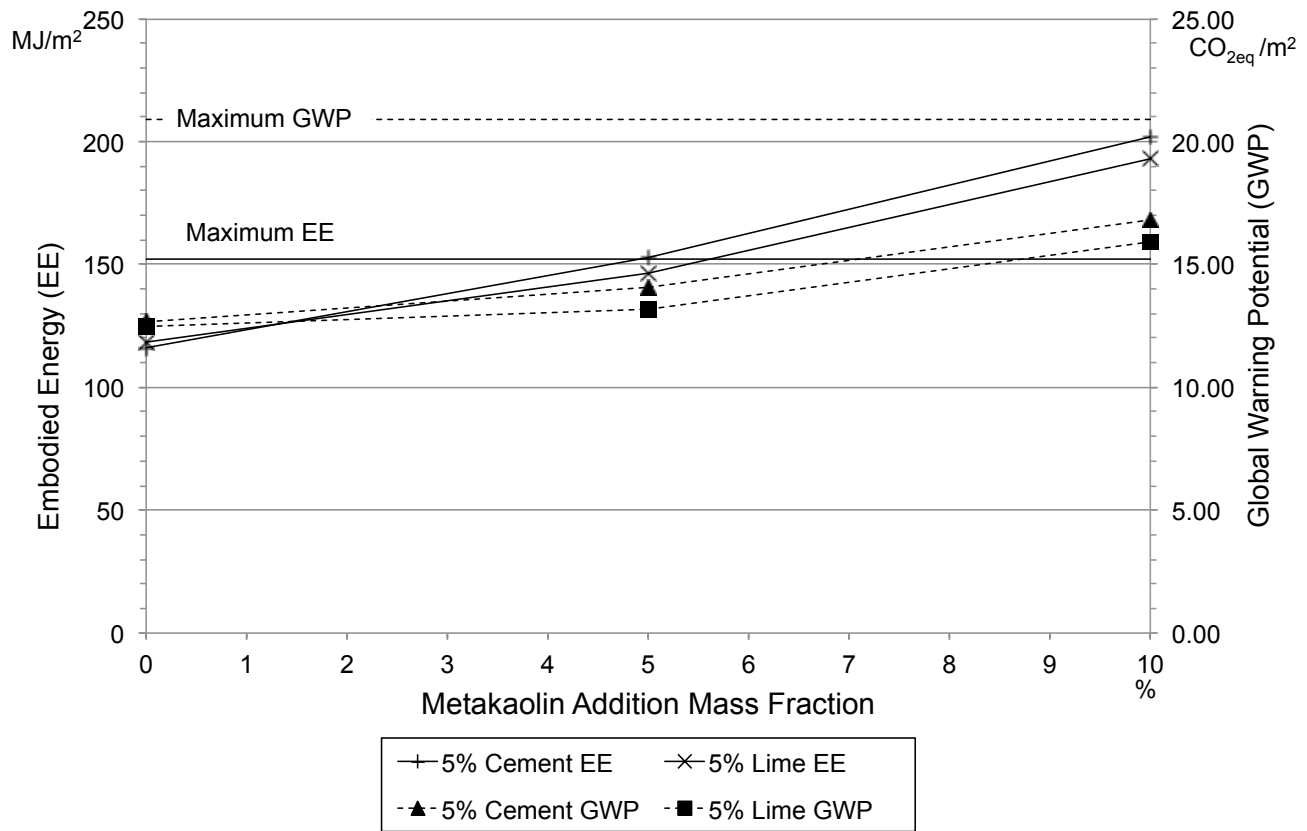


Figure 2 Embodied Energy and GWP of stabilised specimens with additional metakaolin cured at 20°C

4.3 Compressive strength and environmental impact

There are two criteria that must be satisfied for a structurally successful and environmentally beneficial stabiliser to be used for load bearing unfired earth masonry. The structural criteria stipulate a minimum 'dry' and 'wet' compressive strength of 2.9MPa and 1.0MPa respectively (Maskell, D., 2014). The environmental criteria stipulate that the maximum EE and GWP cannot exceed 152.2 MJ/m² and 20.9 CO_{2eq}/m² respectively. Therefore, both these criteria need to be considered together, to define a successful stabilisation method. Figures 3 to 6 display the 28 day compressive strength data against the environmental impact from Table 4 and Figures 1 and 2. By inspection of Table 4, only samples of 5% lime including additional metakaolin exceeded both 'wet' and 'dry' structural criteria under at least one ICT, therefore only these samples were considered potentially acceptable

for use with the given soil. Included are the maximum allowable environmental impact criteria that should not be exceeded and the minimum strength criterion required. Suitable stabilisers are therefore only those within this region.

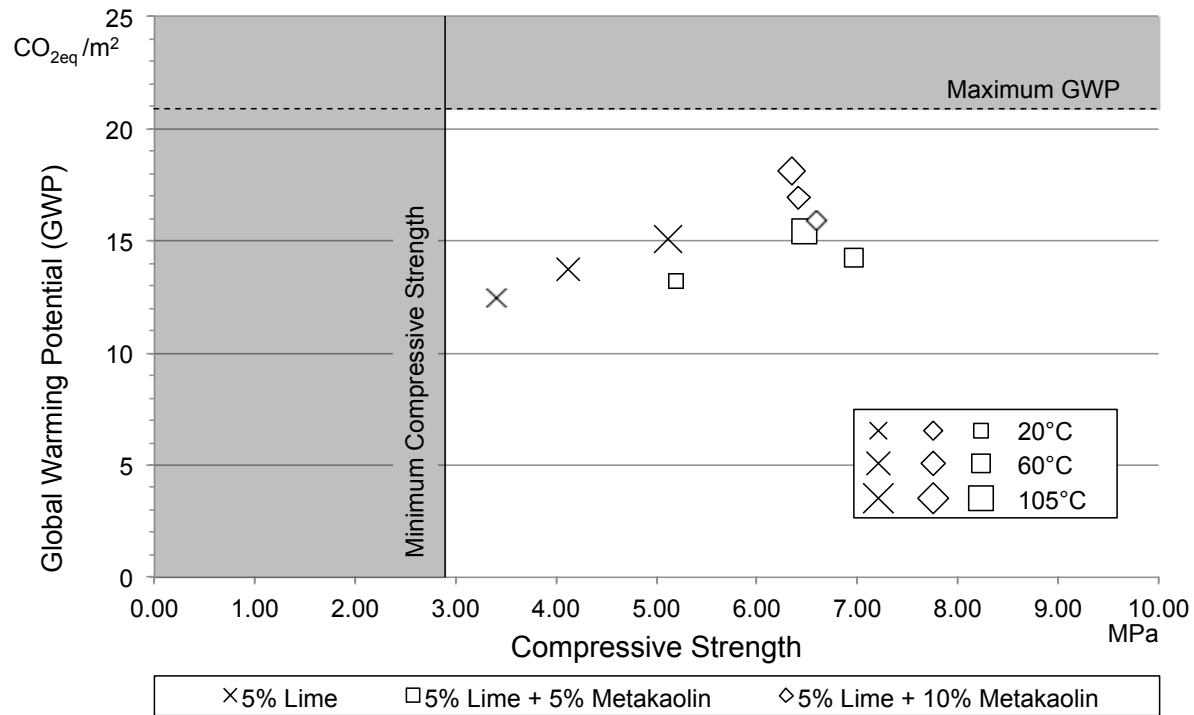


Figure 3 GWP and Dry compressive strength of stabilised earth bricks

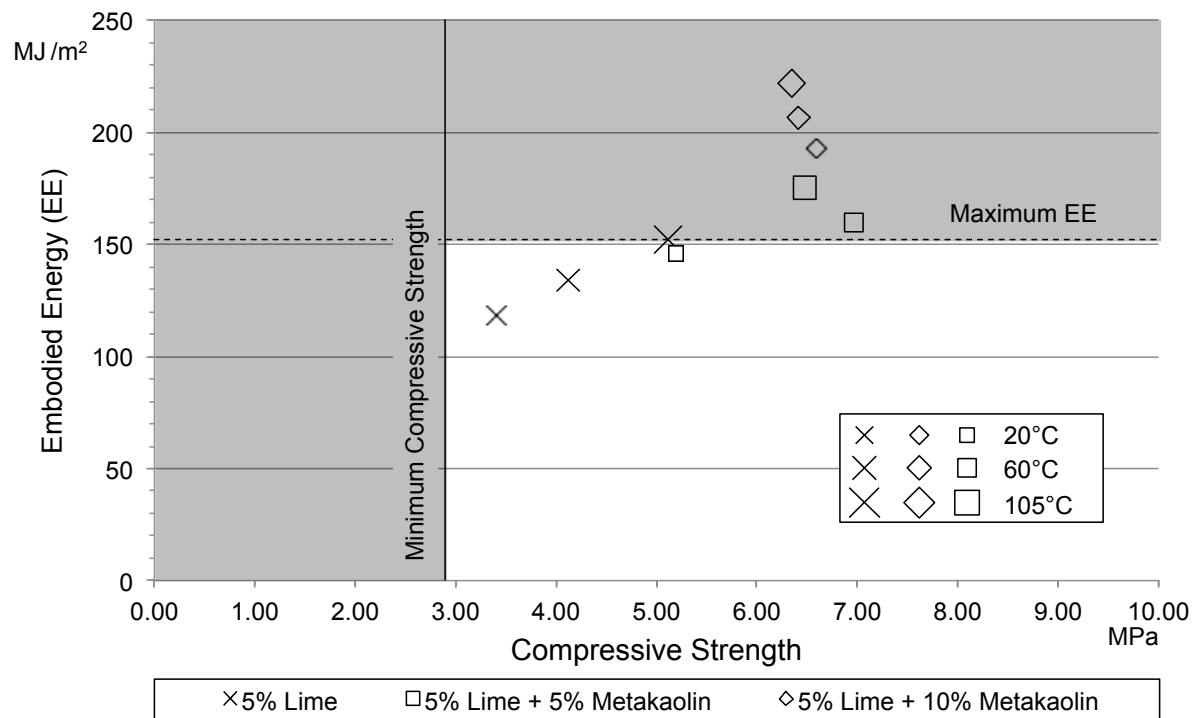


Figure 4 EE and Dry compressive strength of stabilised earth bricks

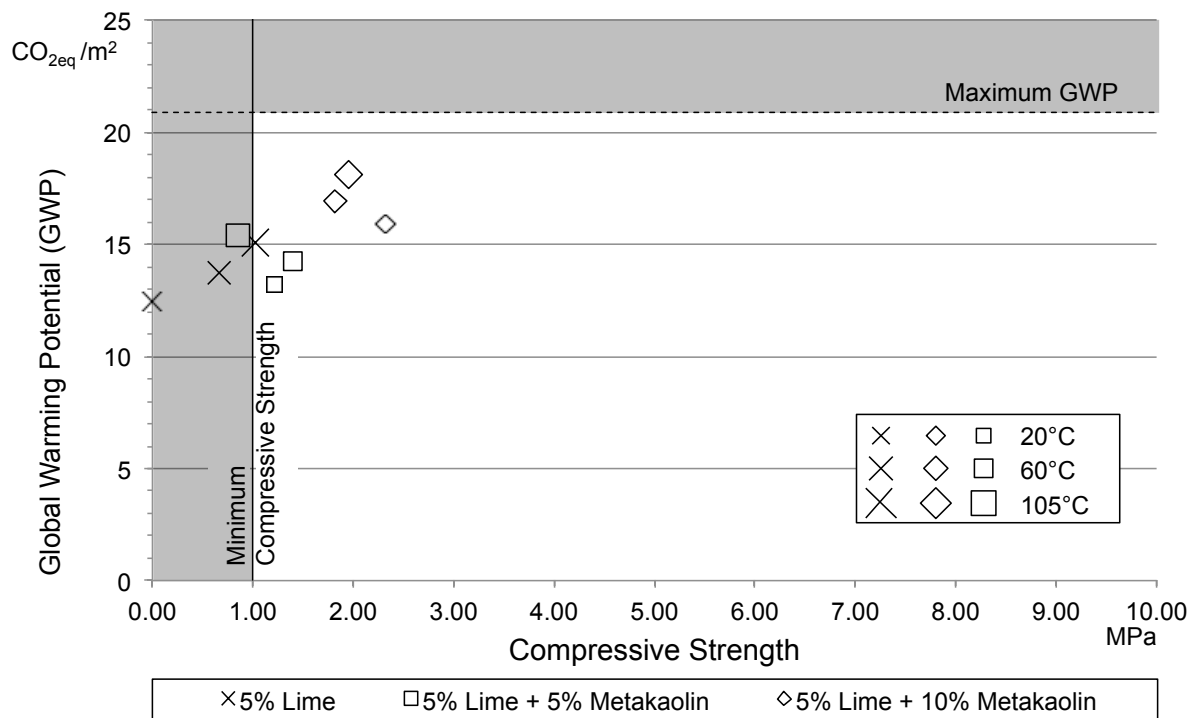


Figure 5 GWP and Wet compressive strength of stabilised earth bricks

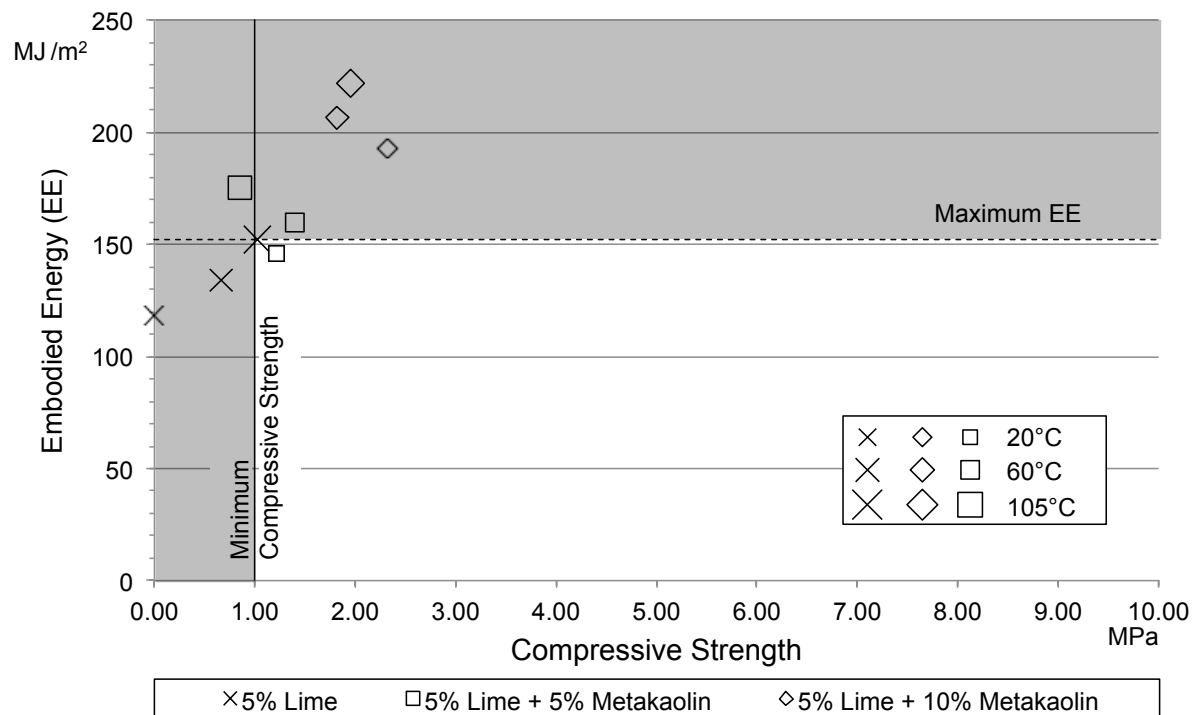


Figure 6 EE and Wet compressive strength of stabilised earth bricks

'Wet' compressive strength is the predominant limiting criteria for successful stabilisation. As seen in Table 4, there are only six specimens that achieved a 1.0MPa 'wet' compressive strength, all of which achieved the minimum 'dry' compressive strength. Of these six specimens only the specimen cured with 5% lime and 5% metakaolin with an ICT of 20°C had an EE and a GWP less than the specified criteria. Considering the argument by Sturgis and Roberts (2010) that only GWP should be used as a proxy for environmental impact then all six specimens become suitable.

All the measured values represent a mean of six specimens for each composition, ICT and curing time. The sample mean is only a point estimate of the true population mean, and therefore the actual mean could be greater or less than the sample means that have been calculated. A confidence interval of the sample mean indicates the range over which the population mean could occur, based on the sample mean, sample standard deviation and the level of risk of assuming that the mean is

outside this range. A similar approach is typically used to calculate characteristic strengths of construction materials. While BS EN 1996:2005 (2009) and BS EN 771-1:2003 (2005) allow for a mean compressive strength of the brick units to be used for the calculation of a characteristic strength of wall, there should be statistical confidence in the mean strengths calculated.

While the lower bound of the confidence interval represents the lowest that the population strength could lie, a more useful measure would be the risk of assuming a population mean is actually lower than a defined value. By inspection, the 'dry' strengths are not critical but only six specimens types achieved 'wet' strengths greater than the criterion of 1 MPa. As these means represent the sample mean of the specimen there is scope that the population mean could be lower than this performance level, determining it unsuccessful. A one sample t-test with an alpha of 0.05 was used to calculate the probability, expressed as a p-value, that the population mean is actually below the 1 MPa criterion and the results are provided in Table 5.

Table 5 p-value of population mean less than 1.00 MPa

Stabiliser 1st Add	Mass Fraction %	Metakaolin Mass Fraction %	ICT °C	Average 'wet' compressive strength MPa	p-value
Lime	5		105	1.02	0.618
Lime	5	5	20	1.22	0.235
			60	1.4	0.029
			20	2.33	0.005
Lime	5	10	60	1.82	0.009
			105	1.95	0.006

Six specimen types with a wet strength greater than 1MPa, two of the specimens have a significant risk of the population mean being less than 1 MPa (Table 5). This is based on the p-value being greater than 0.05, representing there is a minimum allowable 5% risk. These samples are the lime stabilised sample with no additional metakaolin and the lime specimen with 5% metakaolin with an ICT of 20°C. The samples with 5% lime 5% metakaolin with an ICT of 20°C was the only sample that met all the criteria including a reduced EE and GWP, indicating the importance of further full scale testing to potentially lower the level of risk. The other samples have less than a 3% risk of having an

average strength less than 1 MPa. While there were different profiles for strength development depending on the ICT, all of these four specimens exceeded the minimum 'dry' and 'wet' compressive strength by 7 days.

Sensitivity analysis of the environmental impact was undertaken based on changing the all the variables by $\pm 10\%$ that results in values varying by up to $\pm 30\%$. All of the stabilisers fail the EE criterion and the samples with 5% lime 10% metakaolin with an ICT of 60°C and 105°C surpassing the maximum allowable GWP. In consideration of the effect of variability of the strength as shown in Table 5 and the outcome of sensitivity analysis, only two specimens can be considered to meet the required criterion, 5% lime 5% metakaolin with an ICT of 60°C and 5% lime 10% metakaolin with an ICT of 20°C. The reduction in GWP of these specimens is approximately 31.8 % and 24.0%, but an increase in EE of 5.0% and 26.8% respectively compared to dense concrete block work.

5 Summary

There has been limited research on the environmental impacts of earthen construction. A typical LCA would usually consider a cradle-to-grave analysis and focus on several environmental impacts. The focus of this paper was a cradle-to-gate analysis that only considered the EE and GWP using the wall area as the functional unit.

Environmental impact figures from various sources including literature, and datasets were used for the analysis. As such, the results should only be considered indicative rather than absolute, including the estimated impact of metakaolin that was calculated assuming the heating of kaolin. The inventory analysis was used to calculate the EE and GWP of stabilised extruded earth masonry units. The determining factor for both these calculation was the EE that allowed for GWP reductions. There is an argument that the focus should be on GWP reductions, since it is the greenhouse gases that directly effects climate change.

Both structural and environmental impact criteria were considered together determining minimum structural criteria and maximum environmental impact criteria. Only six specimens met the 'dry' and 'wet' compressive strength criteria and the maximum allowable GWP, with only one specimen also meeting the EE criteria. Considering the variability of data both with respect to the measured compressive strength values and the environmental impact values, only two stabilisation methods were deemed suitable, if not considering the EE criteria. While the sample stabilised with 5% lime 5% metakaolin with an ICT of 60°C showed a potential reduction of 31.8% in GWP. Mainstream adoption of stabilised extruded earth masonry will allow for better calculation of the environmental impact ensuring an appropriate structural unfired earth masonry unit.

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